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PREDICTION OF EFFECT OF REFRIGERATION SYSTEM PARAMETERS ON THE PERFORMANCE OF A VAPOUR COMPRESSION REFRIGERATION SYSTEM USING DESIGN OF EXPERIMENTS

C. PRABHA[1], SP. ARUNKUMAR[2] & K. PRABU[3]

[1,3]Department of Mechanical Engineering, Karunya University, Coimbatore, Tamil Nadu, India

[2]Coimbatore Institute of Engineering and Technology, Coimbatore, Tamil Nadu, India

ABSTRACT

The aim of the present work is to study the effects of refrigeration system parameters namely, Evaporating temperature (T_{eva}), Condensing temperature (T_{con}) and mass of the refrigerant charge used (m), on the performance of the system using mathematical models. Three factors and two levels factorial technique were employed for the development of mathematical models to conduct the required experiments. Based on these mathematical models developed for predicting the values of responses, the effect of individual system variables and their significant interaction effects on responses were calculated using MINITAB software. The direct effect of the system variables on the performance was calculated and plotted graphically for the refrigerants R290/R600, R290/R600a, and LPG. The graphs plotted with the help of mathematical models provide satisfactory explanations about the effect of system variables on performance.

KEYWORDS: Refrigeration System Parameters, Mathematical Models, MINITAB Software & Refrigerants

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Original Article

1. INTRODUCTION

Refrigerators are one of the major energy consuming appliances in the household environment [1]. R134a is the most widely used refrigerant in domestic refrigerators, due to its good thermodynamic and thermo physical properties. In India, about 80% of the domestic refrigerators use R134a as refrigerant [2]. But its GWP (Global Warming Potential) effect is 1300. The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) asked for the reduction in emission of six categories of greenhouse gases, including R134a, used as the refrigerant in domestic refrigerators to prevent global warming. [3]. Therefore, according to Kyoto protocol, the consumption of R134a must be seriously reduced [4]. Halogenated refrigerants used in vapor compression based refrigeration, air conditioning and heat pump systems cause greenhouse gas emissions which, in turn, contribute significantly to the global warming. One effective solution to reduce this type of greenhouse gas emissions is by using environment-friendly and energy efficient refrigerants [5].

It is reported that there is no single refrigerant or mixture available to satisfy both the Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) issues. The use of mixtures of refrigerant has proved to be an excellent substitute for the menacing refrigerant R134a.

In this paper an attempt has been made to study the optimum operating conditions of the system such as evaporating temperature (T_{eva}), condensing temperature (T_{con}) and mass of the refrigerant charge used (m), on the performance of a vapour compression refrigeration system using Design of Experiments (DOE).

2. EXPERIMENTAL APPARATUS

2.1. Experimental Set Up

The experimental set-up consists of 200 liter working condition single door refrigerator with a single, hermetically sealed compressor working on 220V, 50 Hz supply. The pressure at salient points of the system is measured by a set of four Bourdon tube type pressure gauges. An air-cooled condenser of the refrigerator is used which is fitted with an air-drier to remove traces of moisture. A set of five capillary tubes having a diameter of 0.78 mm and different lengths (3m, 3.5m, 4m, 4.5m, and 5m) is used. A set of five number hand shut-off valves were fixed before the five capillary tubes to direct the flow from the drier to the required capillary type. The ends of the capillary tubes were connected by a distributed arrangement by brazing onto a common tube on leading the arrangement onto the evaporator. The temperatures at the salient points were measured by calibrated RTD (PT-100) sensors. The total energy consumption of the system, as well as the compressor, is measured by a digital energy meter. The estimation of the COP of the domestic refrigerator was done with the help of an insulated calorimeter setup consisting of a steel drum with exactly the same length of the evaporator used in a domestic refrigerator. The calorimeter is filled with brine solution as a secondary refrigerant. The experimental setup is shown in Figure 1

Figure 1: Experimental Setup of the Domestic Refrigerator

The system was flushed with nitrogen gas to remove the impurities which may affect the performance of the system. The soap bubble test was conducted to check for the leaks. The system was then evacuated of the air before charging with the refrigerant with the help of a vacuum pump. The experimental setup was charged with 110g of R-134a with the help of a digital balance to ensure accuracy. The length of the capillary tube used for R-134a was 3.5m and various tests were carried out on the system.

After completing the test for R-134a the refrigerant was recovered and was filled with the refrigerants R290/R600, R290/R600a, and LPG one after the other into the system after vacuuming the system. The length of the capillary tube was changed for R290/R600, R290/R600a, and LPG.

2.2. Full Factorial Experiments Method

Although the full factorial experiments method is known very well, we present some important steps. For this category of programs, we will use influence factors, with two levels of variation high level (+1) and low level (-1). Having three influence factors, with two levels of variation, we will have to do eight runs. Table 1 shows the matrix program. This type of design allows the estimation of three main effects (A, B and C), the estimation of the effects of three interactions having two influence factors (AB, AC, and BC) and the estimation of the effect of one interaction having three influence factors (ABC) [6]

Table 1: **The 2^3 Factorial Design**

A	B	C
-1	-1	-1
1	-1	-1
-1	1	-1
1	1	-1
-1	-1	1
1	-1	1
-1	1	1
1	1	1

3. EXPERIMENTAL PROCEDURE

The independently controllable variables of the domestic refrigeration system were identified to carry out the experimental work. They are (1) Mass of the refrigerant (m), (2) Condensing temperature (T_{con}) and (3)Evaporating temperature (T_{eva}). Other parameters were set at the constant value. Experiments based on the design of experiments were conducted randomly to avoid systematic errors creeping into the system. The data obtained from those experiments are first used to calculate the performance parameters such as Refrigerating Effect and Compressor Power.

The refrigerating effect is calculated from the relation

$$RE = m_b \times c_{pb} \times \Delta T \quad (3.1)$$

Where, m_b - refers to the mass of the brine solution in kg

C_{pb} - is the specific heat of the brine in kJ/kg k

ΔT - refers to the difference in temperature across the evaporator coil

These calculated performance parameter values of the 8 runs are used to develop the mathematical models and to analyze the performance of the refrigerants R290/R600, R290/600a, and LPG mixture.

4. SELECTION OF MATHEMATICAL MODELS

The response function which represents the performance of domestic refrigeration system can be expressed as

$$R = f(m, T_{con}, T_{eva}) \quad (4.1)$$

Where, R- the response

m - Mass of the refrigerant charge in g

T_{con} - Condensing temperature in ^0C

T_{eva} - Evaporating temperature in ^{0}C

The polynomial equation used to represent the response surface for the k factors is given by

$$R_a = b_o + b_1 (A) + b_2 (B) + b_3(C) + b_4 (AB) + b_5 (AC) + b_6 (BC) + b_7 (ABC) \quad (4.2)$$

Where b_0 is average response value and b_1, b_2….b_7 are co-efficient that depends on main effects and interaction effects. The above model was modified by deleting the factors (AB), which have no effect on the response function

$$R_a = b_o + b_1 (A) + b_2 (B) + b_3(C) + b_4 (AC) + b_5 (BC) + b_6 (ABC) \quad (4.3)$$

By using MINITAB software, significant coefficients were found and a final regression model was developed. The purpose of using this regression model R in this study was not only to investigate the effect over the entire factor but also to locate the region where the response approaches its optimum or near the optimal value of the desired target.

Using the co-efficient, mathematical models were developed for all the refrigerants used in these studies which are given below:

For Refrigerant R290/R600

$$RE = -3.250 - 0.1487\, T_{eva} + 0.0469\, T_{con} + 0.0889.m + 0.00219\, T_{eva}.T_{con} + 0.003372\, T_{eva}.m - 0.000979\, T_{con}.m - 0.000035\, Teva^*.T_{con}.m \quad (4.4)$$

$$CP = -0.309 - 0.0336\, T_{eva} + 0.0065\, T_{con} + 0.00747.m + 0.00054\, T_{eva}.T_{con} + 0.000592\, T_{eva}.m + 0.000119\, T_{con}.m - 0.000005\, T_{eva}.T_{con}.m \quad (4.5)$$

For Refrigerant R290/R600a

$$RE = -3.443 - 0.05203\, T_{eva} + 0.05169\, T_{con} + 0.09211.m - 0.000220\, T_{eva}.T_{con} + 0.001770\, T_{eva}.m - 0.001060\, T_{con}.m + 0.000005\, T_{eva}.T_{con}.m \quad (4.6)$$

$$CP = -0.4866 + 0.05541\, T_{eva} + 0.01075\, T_{con} + 0.01035.m - 0.001602\, T_{eva}.T_{con} - 0.000852\, T_{eva}.m + 0.000049\, T_{con}.m + 0.000030\, T_{eva}.T_{con}.m \quad (4.7)$$

For Refrigerant LPG

$$RE = 0.473 - 0.0097\, T_{eva} - 0.01358\, T_{con} + 0.00707\, m + 0.000070\, T_{eva}.T_{con} + 0.002033\, T_{eva}.m + 0.000031\, T_{con}.m - 0.000033\, T_{eva}.T_{con}.m \quad (4.8)$$

$$CP = 0.559 - 0.0013\, T_{eva} - 0.00795\, T_{con} - 0.00508.m + 0.000025\, T_{eva}.T_{con} + 0.000058\, T_{eva}.m + 0.000187\, T_{con}.m + 0.000002\, T_{eva}.T_{con}.m \quad (4.9)$$

5. RESULTS AND DISCUSSIONS

Mathematical models can be employed to predict the performance of the refrigeration system for the range of parameters used in the investigation by substituting their respective values on different levels. Based on these mathematical models developed for predicting the values of responses the effect of individual system variables and their significant interaction effects on responses were calculated. The direct effect of the system variables on the performance was

calculated and plotted graphically. The graphs plotted with the help of mathematical models provide satisfactory explanations about the effect of system variables on performance. From the developed mathematical models the direct effects of the refrigeration system parameters on the refrigerating capacity, compressor power and coefficient of performance were obtained in Figures 5.1 to 5.4.

5.1. Effect of Parameters on Refrigerating Effect (RE)

The effect of the selected parameters on refrigerating capacity is shown in Figures 5.1 and 5.2. The Pareto chart displays the absolute value of the effects and a reference line. Any effect that extends beyond this line is potentially important. The figure reveals that the factor A (evaporating temperature) which extends beyond the reference line is a most important influencing factor on refrigerating effect. Though factor C which represents the mass of the refrigerant to be charged does not cross the line, but closer to the line indicates the next influencing factor on refrigerating capacity. Factor B represents condensing temperature is the least influencing factor on refrigerating capacity.

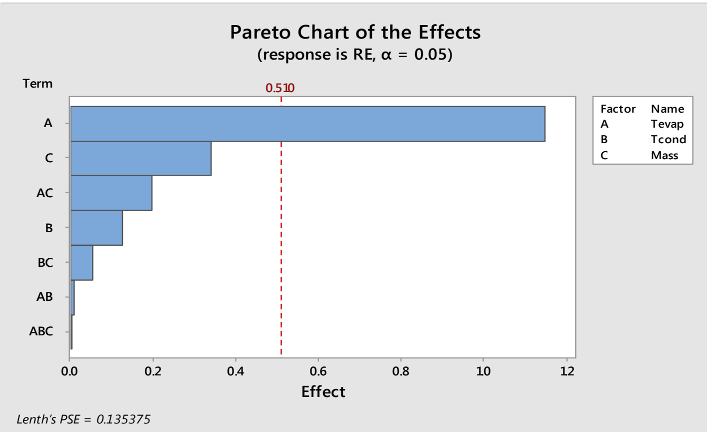

Figure 5.1: Effect of Parameters on RE in Pareto Chart

Figure 5.2 shows the main effect of parameters on the refrigerating capacity at the specified operating conditions. From the Figure, it is observed that the effect of condensing temperature on refrigerating capacity is less significant and an increase of condensing temperature is not affected much on refrigerating capacity. The mass of the refrigerant charged has the significant role on refrigerating capacity. When the mass of refrigerant charged crosses 60g, the system attains mean level of refrigerating capacity which indicates the optimum charging condition of the system. Among the selected parameters the evaporating temperature is the most significant factor in the refrigerating capacity.

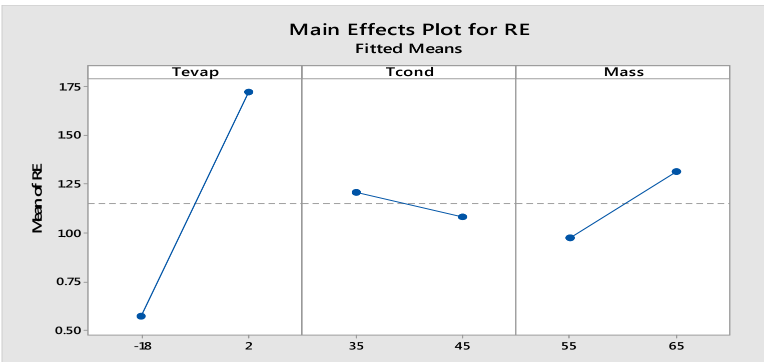

Figure 5.2: Main Effects of Parameters on RE

5.2. Effect of Parameters on Compressor Power (CP)

Pareto chart shown in figure 5.3 revealed that the factor A (evaporating temperature) which crosses the reference line plays a significant effect on compressor power. The factors B and C (condensing temperature and mass of the refrigerant) are having almost similar values on the chart which indicates their similar effect on the compressor power.

Figure 5.4 shows the main effects of parameters on the compressor power at the specified operating conditions. From the Figure, it is observed that the effect of the mass of the refrigerant and condensing temperature on compressor power has the same mean value which indicates their similar effect on the compressor power and increases of their magnitude is not affected much on the compressor. But, an increased mean value of evaporating temperature when compared to other factors revealed that its significant role in the compressor power. It also states that the system will have optimum compressor power consumption when it is operated with the mean evaporating temperature between -18ºC to 2 ºC.

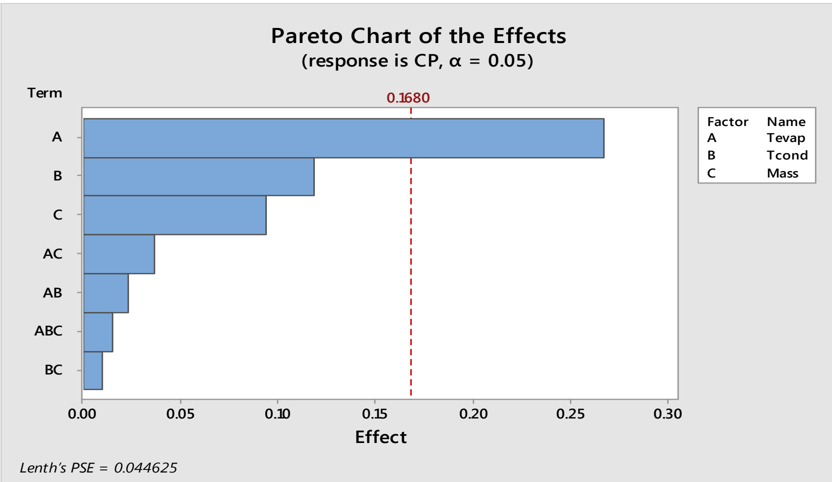

Figure 5.3: Effect of Parameters on CP in Pareto Chart

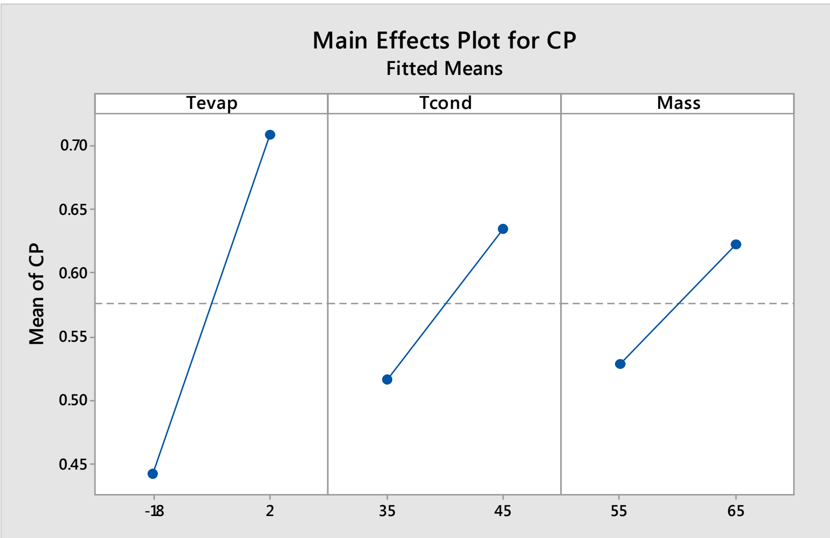

Figure 5.4: Main Effects of Parameters on CP

6. CONCLUSIONS

- The models developed for the performance parameters of a refrigeration system were simple quadratic equations of first order correlating the performance parameters of the system. These developed models can be used for predicting the system performance for any given set of system variables.
- Among the selected parameters, the evaporating temperature is the most influencing factor on refrigerating capacity than the mass of the refrigerant and condensing temperature. As the evaporating temperature increases, the refrigerating capacity of the refrigerant increases due to the higher latent heat of evaporation.
- The descending order of the factors affecting the refrigerating effect of the system is evaporating temperature, a mass of the refrigerant and the condensing temperature.
- The power consumed by the compressor increases as the evaporating temperature increases. The effect of evaporating temperature is significant and its change is affected by the compressor power consumption.
- The effect of a change in mass of the refrigerant and condensing temperature on compressor power is similar and is less significant.

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